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SUMMARY REPORT

ON

TASK ORDER NO. J

Delay Actuator,
Silicone Delay

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October 31, 1957

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SUMMARY REPORT

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INTRODUCTION

During the past several years, many organizations have searched for a cheap, reliable, and reasonably accurate timing device. The Sponsor has had developed a time-delay device which was different from the conventional, expensive mechanical or electronic systems. This device utilized the fluid flow of silicone gum; the volume of gum extruded through an orifice was related to the time period involved in the extrusion. However, because the viscosity and the volume of the gum change considerably with temperature and pressure, the operating range of this device was limited.

Since it was believed that suitable temperature and pressure compensators could be devised, Task Order No. J was undertaken, to develop the existing device further. If the results of the research were favorable, six prototypes of an operating unit were to be fabricated, and production drawings, manufacturing specifications, and an operator's manual were to be prepared. The research directed toward these objectives was conducted during the period from January 8 through October 31, 1957.

DETAILED SUMMARY

This research program was established to develop further a time-delay mechanism which used a silicone fluid as a timing medium and was effective over the temperature range -20 to 120 F. Since information on the properties of silicone fluids was not readily available, current periodicals and representatives of manufacturers of silicone products were consulted. One of the most promising compounds suggested was Viscasil, a silicone fluid with a relatively flat viscosity-temperature curve. Initially, Viscasil 500,000 was selected for study because of its high viscosity and ease of handling.

For the experimental work, three temperature compartments were fabricated, from used refrigeration units, to operate at -20, 50, and 120 F. All of these units were able to maintain temperatures within ± 3 F when the ambient temperature was approximately 70 F.

On the basis of the specified requirements, the ratio of the times for the longest and shortest periods of delay was approximately 6,000 to 1 over a temperature range of -20 to 120 F. Hence, a simple method of adjusting the pressure to extrude the Viscasil was needed, as well as an automatic temperature compensator. At least three devices were visualized. One would use the annular space between two concentric cylinders of different materials as an orifice. If the temperature changed, the size of this orifice would vary, thus altering the flow so as to compensate for the temperature-related change in the viscosity of the fluid. Unfortunately, with such a device, the error in timing would be greater than the allowable ± 10 per cent over the pertinent temperature range of -20 to 120 F. The second device would use two fluids for two different time ranges - 15 minutes to 20 hours and 20 hours to 60 days. The main disadvantage of this experimental unit would be that either two fluids would have to be loaded into the device prior to an operation, or a separate unit would be required for each time range. The third device would use one fluid, Viscasil 500,000; selected concentric springs would supply the force for each time range, and within each range 1 of 7 ports was to be used to achieve a specific time delay. Of the three designs, the third appeared to be the most practical. In addition, a temperature compensator which could automatically change the length of the orifice appeared to be easily adapted to the third design. For simplicity in manufacturing, square-cross-sectioned ports were selected for use in this experimental device.

Since the best idea for a potentially satisfactory timing device involved square-cross-sectioned ports, a study was conducted on the flow characteristics of Viscasil 500,000 through this type of port. The first laboratory unit that was set up contained a closely fitted piston; this was unsatisfactory because of the high force required to overcome the viscous drag of the silicone fluid on the piston. The second laboratory unit used mercury to displace the Viscasil. By adjustment of the height of the mercury column, the pressure for extruding the fluid through a selected port was varied. The second device was found to be quite satisfactory for the purpose.

Flow measurements were made with square-cross-sectioned ports of different cross-sectional areas and lengths at temperatures of -20, 50, and 120 F. Viscosities were calculated and compared with the values obtained from a chart supplied by the manufacturer. In all cases, the calculated values were within ± 5 per cent of the supplied values, respectively. With these results, it was possible to show that a flow equation could be developed that would be applicable to square, rectangular, or circular-cross-sectioned ports.

One of the most promising temperature compensators conceived for this application consisted of three major parts - the main body, which had rectangular slots milled longitudinally on its periphery, the outer sleeve, which enclosed the main body and formed the fourth side of the square-cross-sectioned port, and a bimetallic-thermostat spring, which was to provide the force needed to turn the outer sleeve. Particular areas were cut out of the outer sleeve so that the length of a port could be changed by turning the outer sleeve. Unfortunately, the compensator did not perform satisfactorily. The forces in the Viscasil film between the outer sleeve and the main body, and the ice formed on the parts while in the test cold chamber prevented relative movement. To reduce the drag forces, the clearance between the parts was increased, but this also increased the leakage flow and the error in timing was much higher than the allowable ± 10 per cent.

At this stage, increased effort was concentrated on the design of a suitable temperature compensator. Two types were devised and the error in timing was calculated for both. It appeared that one might be feasible and an experimental model based on this idea was built. This unit included two orifices - one was a temperature-compensating orifice formed by the annular space between two concentric cylinders of different materials, steel and plastic; the other was a simple circular-cross-sectioned port. Calculations based on the data obtained from cursory tests with this model showed that, for the combined flow (i.e., the flow through both orifices), the variation in timing from a mean design value was less than ± 10 per cent over the temperature range -20 to 120 F. However, there was insufficient time to permit conducting a thorough investigation of this experimental unit. The applicability of other materials, the relative size of components, and the effect of the machining tolerances should also be evaluated under various temperature conditions before a prototype can be prepared.

In view of the need for additional data prior to the design and fabrication of prototypes, drawings, specifications, and an operator's manual were not prepared.

ENGINEERING ACTIVITY

The objective of this program was to develop further a time-delay mechanism which used a silicone fluid as the timing medium, so that it would meet the following specifications:

(1) It should have a high degree of reliability, of the order of 99 per cent.

(2) It should be accurate to within ± 10 per cent of the time setting.

(3) It should retain its accuracy over a temperature range of -20 to 120 F.

(4) It should be adjustable over the time range of 15 minutes to 2 months.

(5) It should not weigh more than 1/2 pound.

(6) It should not cost more than $10 in production lots of 10,000.

(7) It should not be larger than about 1 inch in diameter and 4 inches in length.

The engineering activity directed toward the development of such a device is described in detail below.

Literature Search and Fluid Selection

Since data on silicone fluids were not readily available, our library searched The Engineering Index from 1937 to 1957, Chemical Abstracts from 1947 to 1956, and our subject file and catalogue. In addition, two manufacturers - the General Electric Company, Waterford, New York, and Dow Chemical Company, Midland, Michigan - were contacted for information on commercially available silicone fluids. We were unable to find any other companies that could supply useful information on these fluids.

Only one article* provided data which showed the effect of temperature and pressure on the viscosity and density of this material. However, almost from the beginning, silicone putty was eliminated for use in this device because of its undesirable viscosity-temperature characteristics. From the General Electric Company, we learned that a silicone fluid, Viscasil 500,000, has a relatively flat viscosity-temperature curve. Also, this material could be readily mixed with the extremely viscous Silicone Gum SE-76 to obtain fluids with a viscosity intermediate between those of the lightest Viscasil and of the gum. Based on this information, Viscasil 500,000 was selected for experimental evaluation.

Laboratory Equipment

While the literature search was being conducted, temperature chambers for the experimental work were considered. It was decided that temperatures of -20, 50, and 120 F would be sufficient to permit covering the required range of -20 to 120 F.

A search of our facilities was made for suitable experimental equipment; because of space limitations, security, and economy, we ultimately fabricated the temperature chambers. Two used refrigerators were modified to maintain temperatures of 50 and 120 F, while a used 2-cubic-foot freezer was set up to maintain a temperature of -20 F. Figure 1 shows the three experimental temperature compartments.

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*"Silicone Putty as an Engineering Material", F. W. Spooner, <u>Product Engineering</u>, January, 1950, Vol 21, pp 90-93.

Figure 1. Three Temperature Chambers

The temperature variation of these compartments was less than ± 3 degrees, with an ambient temperature of 70 F. These units were considered to be satisfactory for evaluating the properties of Viscasil 500,000 and for ultimately determining the performance of the experimental timing device.

Preliminary Design Considerations

Preliminary calculations were made to obtain some indication of the type of device necessary to fulfill the design specifications. Since the ratio of the longest to the shortest time period of interest was approximately 6,000 to 1, some means had to be devised to permit the selection of intermediate times. Also, the variation in viscosity of the fluid over the temperature range of interest required some kind of temperature compensation for any given time-period selection.

The basis of the preliminary design considered was the time involved in the extrusion of Viscasil 500,000 through an orifice. Preliminary calculations showed that an extremely low pressure would extrude the Viscasil through a sharp-edged orifice. It appeared that a "pipe" orifice might be more suitable in this application, since its length would offer additional resistance to flow. A higher resistance would require an increased pressure, in order to achieve extrusion, and a higher pressure could be controlled more easily.

In the development of the flow equation, it was assumed that the shear stress was proportional to the rate of shear. Hence, the time of flow varied with the pressure differential, the volume of material extruded, the radius and the length of the orifice, and the viscosity of the fluid. All of these factors were considered separately and together to determine if any could be easily varied and, hence, be used for pressure or temperature compensation. A number of possible solutions to the problem were conceived; of these, three are described below.

Annular-Space Orifice

One system would use the clearance space between two cylinders of different materials. With properly selected dimensions and materials for the cylinders, variations of the temperature could be expected to alter the amount of clearance space and, thus, control the flow so as to compensate for the associated changes in the viscosity of the Viscasil. It would be possible to design a device from aluminum and steel that had an error of ± 10 per cent in delay time when operating over a temperature range of -10 to 109 F. However, in order to cover the range of time periods of interest for a given orifice length, the ratio of the average pressures exerted on the Viscasil for the shortest and longest time periods corresponded to about 6,000 to 1. Unfortunately, no satisfactory method of handling such a large pressure variation was devised.

Two-Fluid System

From the beginning it was realized that, to vary the time period in a single device, some simple method of adjusting the pressure was required. In one possible solution to the problem, the total time period of interest was divided into two ranges - one from 15 minutes to 20 hours and the other from 20 hours to 60 days. This reduced the associated pressure ratio to 80 to 1. A further reduction in this pressure ratio to 1 to 1 was accomplished by the use of a different fluid for each of the two time ranges. Theoretically, two materials - Viscasil 210,000 for the shorter time range and Silicone Gum SE-76 for the longer range - appeared to be satisfactory. However, the use of two fluids would not be conducive to simplicity. Either the proper fluid, depending on the delay period of interest, would have to be loaded just prior to an operation, or separate units would be required for each time range. Because of the high viscosity of the fluids, the loading operation would be cumbersome and time consuming. Consequently, no further work was done with this idea.

Multiple-Port System

The third type of device provided combined ease of production and simplicity. One fluid was to be used, namely, Viscasil 500,000. Separate concentric springs for the two time ranges were to be enclosed within the unit and either one could be selected for use depending on the time-delay period desired. In order to permit selecting the desired time period within either one of the two ranges, seven ports were to be available. The smallest port and the weak spring (0.375-lb/in. spring rate) would permit a selection of a time delay from within the range 32 to 64 days. This same port with the strong spring (15.15-lb/in. spring rate) would provide a time delay within the range 16 to 32 hrs; to obtain a particular time delay within either range, the springs could be adjusted appropriately. This unit also could have a temperature-compensating device which automatically changed the length of the port so as to eliminate the effects of associated changes in the viscosity of the fluid.

Of the three designs, the multiple-port system appeared to be the most practical. The basic ideas indicated above were subsequently incorporated in the design of an experimental device. For simplicity in production and for ease of control over the temperature range of interest, a square-cross-sectioned port appeared to be the most applicable.

Design and Fabrication of Flow-Measurement Units

Since the most promising design for an appropriate timing device involved square-cross-sectioned ports, laboratory units were set up to facilitate the accurate determination of the flow characteristics of Viscasil 500,000 through this type of port. In the two experimental units which were used in this investigation, the factors which affected the flow, except for those under study, were either isolated or minimized.

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Figure 2. Device for Measuring Flow Through Square-Cross-Sectioned Ports

Piston-Type Unit

The first test unit had a closely fitted, weighted piston which exerted the extruding pressure on the fluid. The 0.003-inch diametral clearance between the piston and the associated cylinder limited the leakage through this space to less than 1 per cent of the minimum flow. Any one of seven ports could be selected for test. The ports were about the same sizes as those expected to be applicable to the prototype.

In the initial experiment using this laboratory unit, it was found that the force required to overcome the resistance in the Viscasil film between the cylinder and the piston was much higher than had been anticipated. Though the clearance between the parts could have been increased to reduce the shearing force, this was not considered to be a satisfactory method for improving this device so as to permit evaluation of the flow characteristics of Viscasil 500,000. Further work with this unit was abandoned.

Mercury-Displacement Unit

In the second laboratory device, mercury was used to force the Viscasil through the ports. By regulating the height of a mercury column, the pressure for extruding the fluid through a selected port could be varied.

Figure 1 (center) shows how the mercury was fed to the port-containing portion of the test unit when located in the temperature chambers. Figure 2 shows a disassembly of the port-containing portion of the test unit which was filled with Viscasil.

The mercury was fed directly into the bottom of a space between two concentric cylinders in the portion of the unit shown in Figure 2. As the mercury level rose in this space, it exerted a pressure on the Viscasil 500,000, which completely filled the remainder of the space. The pressure thus exerted then forced the Viscasil through the port selected for the particular experiment, and the rate of flow was related to the rate of change of the mercury-column height in a graduated pipette (Figure 1). For repeat tests, the port-bearing portion of the unit was refilled at the top with Viscasil by means of a grease gun.

Flow Measurements

Considerable data were needed on the flow characteristics of Viscasil through square-cross-sectioned ports under various temperature conditions before a device could be designed to fulfill the specifications. If the cross-section area and the length of the ports were to be varied, experimental data were needed to permit determination of the limiting area-to-length ratio of the port for which the flow equation was still applicable. It appeared that, if the ratio was too high, then the port functioned as a sharp-edged orifice. As was mentioned previously, a sharp-edged orifice was not considered to be satisfactory in this application because of the low pressures involved.

Experiments were conducted with the above-described mercury-displacement unit. However, before satisfactory results were obtained, two major problems developed. First, the Viscasil flow rate decreased progressively in consecutive tests even though the test conditions were identical. The difficulty was ultimately attributed to the low-pressure type of rubber hose used for feeding in the mercury (Figure 1); it appeared that the hose acted as an accumulator. This low-pressure-type hose was replaced with a high-pressure type and the difficulty was eliminated. Second, spurious flow-rate data were consistently obtained as a result of Viscasil leakage around the port seals. The port assemblies contained six different ports, and each port had a separate seal. In the first few experiments, leakage between the ports affected the results obtained; this leakage was quite consistent, so it was not easily detected. It was only after the port seals were improved that accurate, reliable measurements were achieved.

At first it was thought that a simple plot of the measurements showing the change in height of the mercury column and the time would be sufficient for evaluating the flow characteristics of the fluid. However, this was not the case. It became necessary to develop an equation which could be applied to the system used in the experimental work and which could also be used in calculating the data needed in connection with the prototype design.

To determine how accurately the flow was controlled by changing the port cross-section area, the calculated viscosity was compared with the viscosity value taken from the data supplied by the General Electric Company. For 120 F, the calculated values varied from 0.044 to 0.049 $lb\text{-}sec/in.^2$, and compared favorably with the value of 0.048 lb-sec/in.^{2}, provided by the General Electric data. For -20 F, the calculated viscosities for two ports were 0.268 and 0.264 lb-sec/in.^{2}, as compared with the General Electric value of 0.270 lb-sec/in.^{2}. For 50 F, the results were equally good; the calculated values were 0.099 and 0.098 lb-sec/in.^{2}, and the General Electric value was 0.099 lb-sec/in.^{2}. From this work, it appeared that the flow through square-cross-sectioned ports could be accurately calculated if the port physical dimensions and the fluid properties were known. Since the appropriate equation was fairly general, it appeared that flow through circular-cross-sectioned ports could also be calculated with it.

Experiments With Temperature Compensators

To compensate for the variation in viscosity with temperature, a simple and accurate temperature compensator had to be included in the unit. The device had to convert a linear change in temperature to a complex logarithmic form because of the viscosity-temperature relationship of Viscasil 500,000. It was established that one of the convenient ways to compensate for variations in viscosity with temperature was to change the length of the orifice automatically.

Rotating-Sleeve Type

One of the most promising temperature compensators that fulfilled this design criterion is shown in Figure 3. This rotating-sleeve-type unit consisted of a main body, an outer sleeve, and a

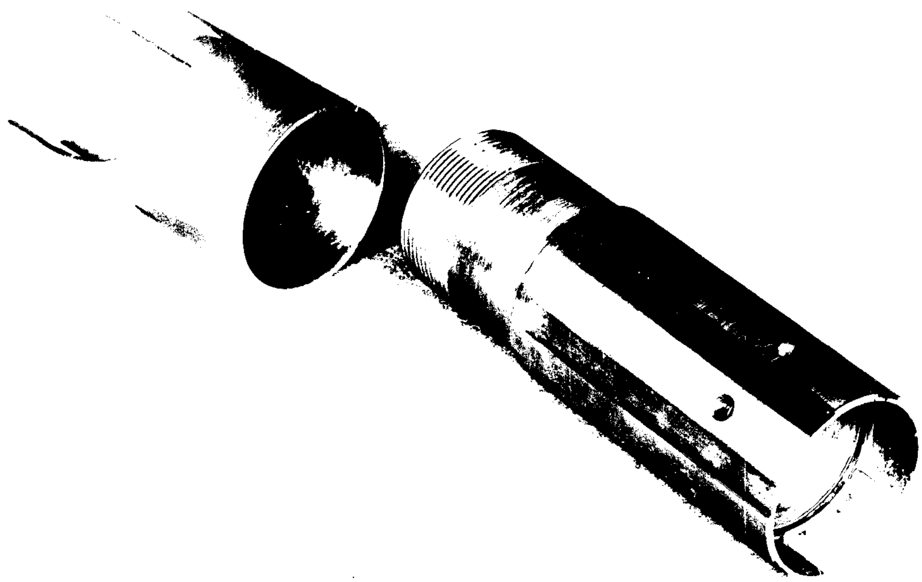

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Figure 3. Rotating-Sleeve Type of Temperature Compensator

bimetallic-thermostat spring (not shown in Figure 3). The main body had three-sided ports milled longitudinally on its outer periphery; one of these ports is shown at the top of the main body in Figure 3. The outer sleeve was free to turn on the main body and also formed the fourth side of the square-cross-sectioned port. Selected volumes were milled from the outer sleeve so that rotation of the sleeve would change the effective length of the port. The bimetallic-thermostat spring was to produce the force needed to turn the outer sleeve.

Experiments were made to determine the feasibility of this design. First, the outer sleeve and the main body were lapped together in order to obtain a clearance of approximately 0.0003 inch. Unfortunately, the thermostat spring recommended for this application by the supplier (W. M. Chace, Detroit, Michigan) was not able to turn the outer sleeve even when the temperature changed by as much as 50 F; the high resistance was created by the force in the Viscasil film generally and by the ice formed on the two parts (sleeve and main body) during exposure to a lower temperature (25 F). When the main body was coated with Viscasil, the ice formation was minimized, but the drag forces were increased.

We were able to reduce these drag forces by increasing the clearance space to 0.001 inch. Measurements indicated that, at a temperature of 85 F, a force of approximately 0.5 pound was required to turn the outer sleeve at a rate of 0.0023 inch per second. However, with a 0.001-inch clearance space, the leakage flow rate was more than twice the flow rate through the port when the Viscasil was subjected to the maximum design pressure.

Further, small machining errors had a pronounced effect on the flow rate for this device. Thus, when the clearance space was increased from 0.0003 inch to 0.0005 inch, the leakage flow rate increased from about 5 per cent to about 20 per cent of the total flow rate. In addition, the 0.0003-inch clearance necessitated a force of about 7 pounds, in order to just turn the outer sleeve at a temperature of -20 F. Calculations showed that a bimetallic-thermostat spring 7 inches wide was needed in order to exert this force.

It appeared from these experiments that this type of temperature compensator had serious practical limitations. A thermostat spring of an impractically large size was required in order to overcome the drag forces, and also, even though the clearance space could be kept relatively small, the leakage flow rate would vary too much as a result of small machining errors or inaccuracies.

Other Types of Temperature Compensators

Our efforts were subsequently concentrated on the design of a better temperature compensator. Two types were conceived. The error in timing was calculated for both of these designs and it appears that one of them might be feasible.

__Variable-Port-Area Orifice__. A temperature compensator was conceived that would change the port cross-section area so as to restrict the flow as the temperature increased. For the initial calculations, a triangular orifice with one movable side made of neoprene was visualized. The force which would move the neoprene side was to be developed by the expansion and contraction of a predetermined volume of mercury. Because the mathematics for this system was rather complex, the accuracy of this device was only estimated. It is expected that the time delays obtained in such a unit would vary by about ± 10 per cent of the minimum design value over the temperature range -20 to 120 F; this was considered to be excessive, and the idea was set aside.

Double-Orifice Unit. Ideally, a temperature compensator should not have any moving parts. One design appeared to meet this criterion by using two orifices. One would be a temperature-compensating orifice formed by the annular space between two concentric cylinders of different materials, steel and plastic; and the other would be a simple circular-cross-sectioned port. As the temperature changed, the size of the annular orifice would vary, while the simple port would be virtually unaffected. The total flow would be the combined flow through both of these orifices. Over the pertinent temperature range of -20 to 120 F, the variation of flow from a mean design value was calculated to be only 4.4 per cent. However, there was one serious drawback; the ratio of the average pressures exerted on the fluid by the springs corresponding to the shortest and to the longest time periods was approximately 6,000 to 1. Fortunately, in this system, it is possible to reduce this ratio considerably by changing the materials used for the compensator. As currently visualized for the final design, one of several assemblies, each covering a particular time range, would be inserted into the main body just before the device was used.

To verify the theories postulated, an experimental cylindrical unit with a steel body and a concentric plastic insert was tested under three temperature conditions, namely, -20, 50, and 120 F. The purpose of the experiments was to determine the degree of control of flow through an annular orifice, as well as the accuracy of the flow equation for this system. The primary source of potential difficulty in this design lies in the fact that, if the inner component shifted radially so that the two components are in line contact tangentially, the flow can increase to a value more than twice that for concentric pieces. The experimental results obtained from these tests were quite encouraging. The clearance space at different temperatures, as calculated on the basis of the flow equation, was within ± 5 per cent of the values calculated from the thermal-expansion data for the two materials.

It appears from these preliminary experiments that the double-orifice temperature compensator would probably be feasible. However, some caution is indicated, as additional experiments are required. The coefficient of thermal expansion of different materials, the relative size of the components, and the effect of machining inaccuracies or errors should be investigated before a final evaluation is reached.

CONCLUSIONS

Although a device which completely satisfied the specifications was not developed, basic criteria were established for the design of a potentially successful unit.

The major conclusions reached were:

(1) Within the range of the conditions investigated in the course of the experimental work, the flow of Viscasil-type fluids through pipe orifices can be predicted accurately by standard flow equations.

(2) If the temperature compensator of such a unit is in contact with a high-viscosity fluid, it should not have to move in the course of performing its function.

(3) The ports of such a device should not have any movable sides; otherwise, the leakage that results is excessive.

(4) The piston in such a device should not contain any O-rings or packings. (One promising method of sealing a piston without introducing excessive frictional forces would be to use a Bellofram piston seal .)

RECOMMENDATIONS FOR FUTURE WORK

With the information obtained from this project, it is believed that an inexpensive, practical time-delay mechanism could be developed that would fulfill the design specifications. However, before the design of such a unit was finalized, additional experiments with the double-orifice temperature compensator should be conducted. Although the principles involved now have a firm foundation, certain practical problems may be limiting. The effect of these problems, in particular, machining tolerances, should be established in order to determine their influence on the accuracy of the mechanism. Further, while preliminary calculations indicate that the Bellofram piston seal would be satisfactory in any pertinent mechanism, the performance of this seal should be evaluated in the time-delay device under simulated operating conditions.